

# HOW DOES MANNING'S ROUGHNESS COEFFICIENT CHANGE WITH VARYING WIDTHS?

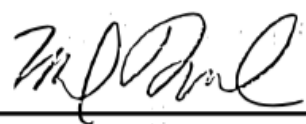
Research Thesis

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By

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Approved by

A handwritten signature in black ink, appearing to read 'M. Durand', written over a horizontal line.

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## **ABSTRACT**

The use of remote sensing technology is increasingly important in today's society, especially with respect to measuring water stored in rivers, lakes, and wetlands. The purpose of the Surface Water and Ocean Topography (SWOT) mission (which will launch in 2020) is to enhance our understanding of ocean circulation, to measure hydrologic storage change in global lakes, and to estimate river discharge. SWOT uses a type of altimetry that allows it to measure temporal and spatial variations; it has been proposed by a group of hydrologists from American universities to use a form of Manning's equation for the SWOT discharge estimates. The research reported herein focused on determining whether Manning's roughness coefficient changes as a function of discharge and stage. River height and width datasets collected at 20 stations on the Olentangy River were utilized to assess variations in the roughness coefficient. The measurements allowed for a highly precise measurement of river surface slope for five sub-reaches. Together with gaged discharge above the reach, these datasets allowed inference of the roughness coefficient for the five sub-reaches. For all sub-reaches, roughness coefficient varied by approximately a factor of two to three throughout the study period, with more variability in the downstream reaches where hydraulic regime is controlled by low-head dams. For the the steeper upstream reaches, roughness coefficient was not well-correlated with flow, while roughness coefficient for the downstream reaches showed a high correlation with flow.

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## **INTRODUCTION**

Water has been a valuable resource since the dawn of time and society has invested significantly in infrastructure such as stream gages for characterizing river flow. Nonetheless, our ability to characterize global patterns of streamflow is surprisingly poor. The Surface Water and Ocean Topography mission (SWOT) will launch in 2020, and will utilize satellite technology to accurately determine how much water is travelling in different environments across the globe. SWOT will measure how bodies of water evolve over time by measuring river height (using altimetry) and width. SWOT will also measure river surface slope. To do this, scientists are performing research to develop river discharge algorithms.

The so-called Manning's equation has been proposed for use in river discharge algorithm. Within Manning's equation is the Manning roughness coefficient or  $n$  which is often empirically derived and is difficult to determine from quantitative sources (Phillips and Tadayon, 2006). This thesis hopes to assess changes in the roughness coefficient during hydraulic events by noting the changes in  $n$ .

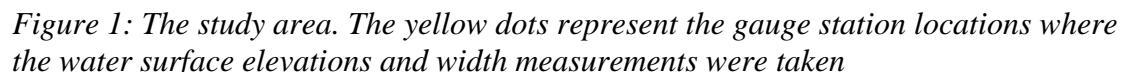
### **Objectives**

Although Manning's roughness coefficient is often determined through observation or evaluation of images of the river, many people have tried to calculate an answer from measured variables (Phillips and Tadayon, 2006; Ding et al., 2004). For the Olentangy River in Columbus, Ohio, several civil engineering projects have changed the natural flow of the river (FMSM Engineers, 2005). Studying the effects of these civil engineering projects on the Olentangy could be useful to apply to other rivers with similar installations.

The purpose of this study is determine whether  $n$  changes and if there are determinable differences in the reaches above or below the lowhead dams since the dams may change flow.

Additionally, changes in  $n$  and subsequent correlation or lack thereof with WSE and  $Q$  reflect accurate measurements and calculations.

The study area is a 6.5 km reach on the Olentangy River in Columbus, Ohio with a watershed area of 530 mi<sup>2</sup>. The river is controlled by the Delaware Dam approximately 32 km upstream from the reach. Figure 1 shows the study reach along with 20 measurement stations described in the next section. The stations are about 300 meters apart and broken up into 5 sub-reaches. There are 2 low-head dams: one at 5.5 km and 6.4 km; the hydraulics of sub-reaches 4 and 5 are controlled by these lowhead dams, respectively. The river is accessed for measurements via the Olentangy Bike Trail. There are major rivers that join the Olentangy River within the study area.



## METHODS

### Overview

Two different sets of methods were used to gather data. For the first year, the goal was to obtain width and water surface elevations, while the goal for the second year was to obtain depths of the river and water surface elevation. Depth was collected to calculate the base river cross-sectional area (Tinkler, 1982). USGS flow data were also utilized. All measurements were used in a modified Manning's equation (shown below).

$$Q = \frac{1}{n} (A_0 + \delta A)^{\frac{5}{3}} W^{-\frac{2}{3}} S^{\frac{1}{2}}$$

where  $Q$  is the river discharge,  $n$  is the roughness coefficient,  $A_0$  is the base-flow cross-sectional area,  $\delta A$ , the change of cross-sectional area based on a trapezoidal approximation,  $S$  is the river surface slope, and  $W$  is the river width (Durand et al., 2014). Discharge was obtained from the USGS station at Worthington, and lagged in time to account for travel time to our study area.

### Width and Water Surface Elevations

In 2013 and 2014, width and water surface elevation (WSE) data were gathered via 20 gauges in the study area using the gauges, GPS measurements, and USGS data. Continuous WSE at each station was determined by combining the water depth measurements made by the Solinst level loggers with weekly measurements of WSE made by a Leica Viva GS15 GPS with RTK streaming to correct for atmospheric conditions.

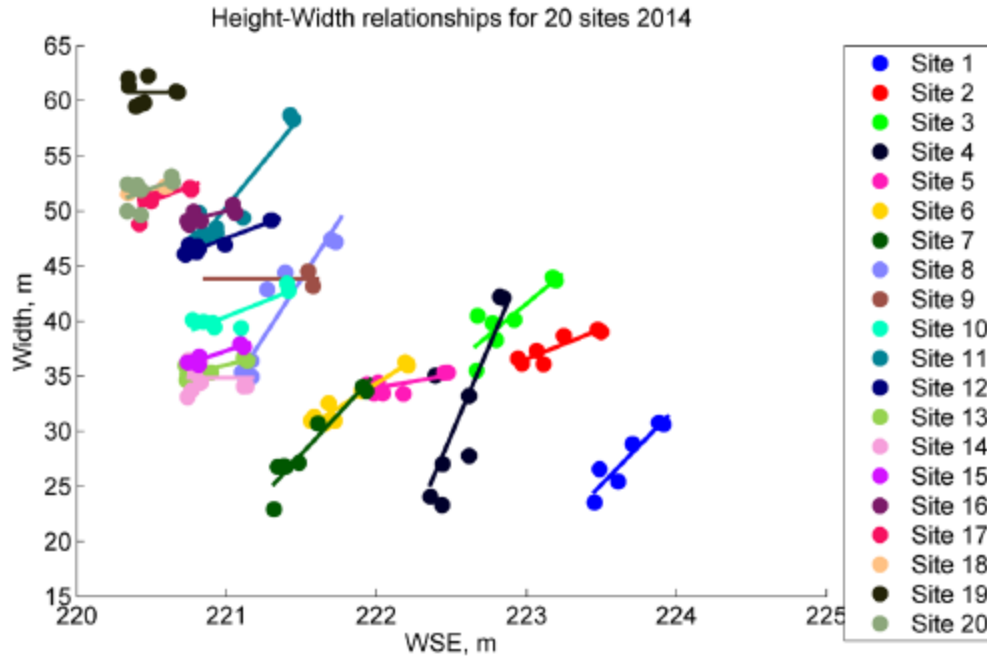
Width measurements were taken weekly and at varying WSE. The measurements were gathered using a laser rangefinder at each of the gauge stations.



*Figure 2: An image showing how the width measurements were taken. Fixed points were selected perpendicular to flow and then measured 5 times at each station, at least once per week and during storm events.*

Width-height relationships were modeled for each gauge by a linear fit. This allows a continuous timeseries of width to be determined. It also allows for validation of the width measurements.

This is shown by the positive correlation of the widths increasing as the height increases.



*Figure 3: Width-height relationships were created and plotted with a linear fit.*

Time series were then calculated using elevations from the combination of GPS measurements and data from the Solnist level-loggers at each gauge station.

### Reach Averages and $\delta A$

After all data were collected, reach averages were calculated. This allowed us not only to garner an overall picture of the river, but also to simultaneously rule out single, erroneous data points.

After all data were collected, it is possible to revisit  $\delta A$  which we can calculate now that we have all measured data points. Doing so shows how the timeseries are different in the lower and upper reaches. This was also done for slope which can be calculated using the overall elevation change over the length of the reach. These time series in particular help in visualize each part of Manning's equation.

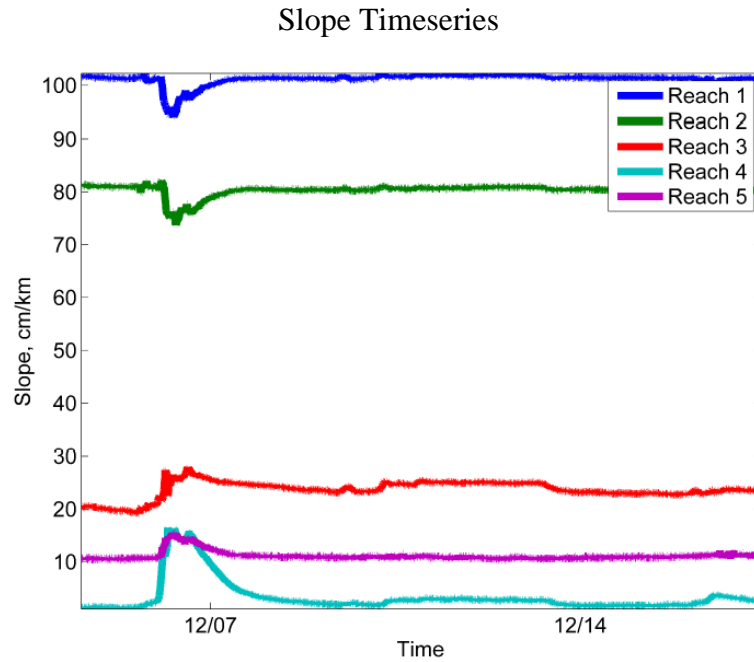


Figure 4: Slope timeseries. This time series helps visualize the temporal changes in slope.

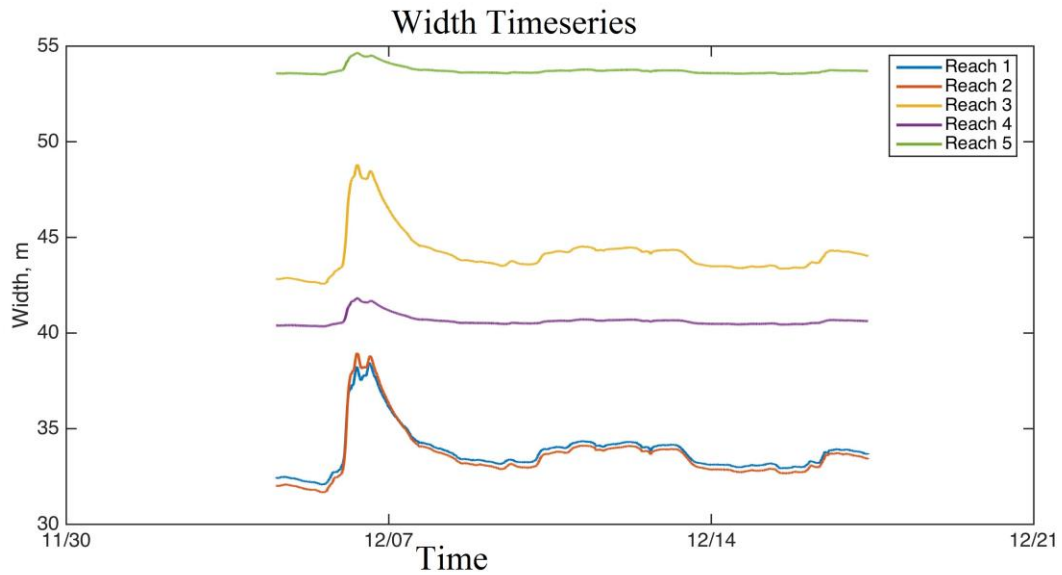


Figure 5: Width timeseries over the reach average. The reach averages were used to rule out error in single data points

### Finding $A_0$

Since  $A_0$  is needed to determine the entire bathymetry of the river, two methods were attempted to find  $A_0$ . First, area was calculated for the five subreaches using a least squares method.

Specifically, time-invariant estimates of  $n$  along with  $A_0$  values were calculated. Second, we have begun collecting bathymetry measurements using a kayak and depth sounder; these are ongoing and are described in the future work section.

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Table 1: Optimized  $A_0$  Values

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Reach	Optimized Values ( $m^2$ )
1	4.46
2	5.30
3	8.98
4	16.74
5	16.38

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## RESULTS

### Width Precision

One major part of this project was collection of ample amounts of data, specifically width data, to allow thorough assessment of changes in  $n$ . These data are used in the calculation of  $A_0$ , so accuracy is a must. When compared to the best fit lines calculated for the width-height comparison graph in Figure 3, there is a very small margin of error. Since the measured points are precise within about  $\pm 1$  meters, it can be assumed that discrepancies in  $A_0$  does not come from the width measurements.

### Changes in $n$

A first look at the data shows that  $n$  does change over the entire reach of the river. To find this, a calculated best fit  $A_0$  was chosen and paired with a fixed  $n$ . These two were then fit using a non-linear least squares algorithm. From this, it is possible to solve for a calculated  $\tilde{n}$ , which is defined as the roughness coefficient that completes Manning's equation for the sub-reaches. Note that it has been found in the literature that the simple average  $n$  across many cross-sections does not average to  $\tilde{n}$  (Durand et al., 2016).

Variances of  $\tilde{n}$  were then compared to discharge and WSE for all 5 reaches which were calculated using an  $A_0$  found through best fit. This is adequate to determine if  $n$  is changing but not to assess Manning's Equation. The data points in the upper three reaches vary considerably, with values ranging from 0.01 to a value of 0.06 or higher. However, these changes are not well-correlated with  $Q$ . For the lower two reaches, approximately the same range of  $\tilde{n}$  was observed, but the values are highly dependent on  $Q$ , with higher values of  $\tilde{n}$  at low flow.

### Correlations of $n$ with $Q$ and WSE

In the charts comparing  $\tilde{n}$  to  $Q$ , there is a noticeable correlation (Figure 6). In reaches 1, 2, and 3, there appears to be no (or very little) correlation while in reaches 4 and 5, this correlation follows a more logarithmic relationship. These same correlations are present in the figures comparing  $\tilde{n}$  and WSE but to a lesser extent (Figure 7). The data are more erratic and less defined than in the discharge comparisons. It should be noted that while the upper three reaches vary less, there could still be an error with the calculations due to flawed measurements. This may have to do with the difference in the amount and quality of measurements used in the calculations used to achieve each variable for comparison. Inaccurate measurements would lead to improper modeling of the river channel and therefore  $n$  variations that are skewed.

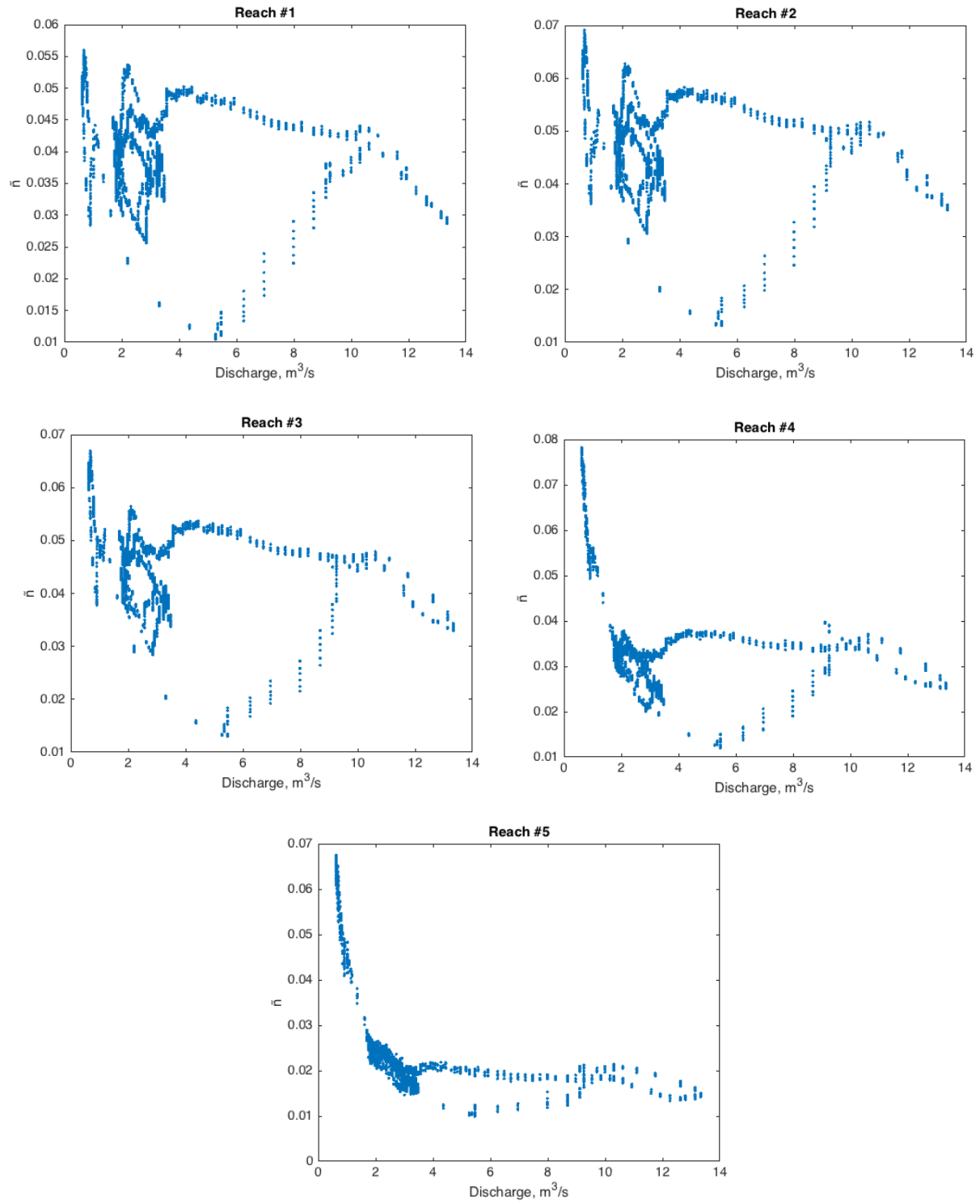


Figure 6:  $\hat{n}$  vs.  $Q$  for reaches 1-5

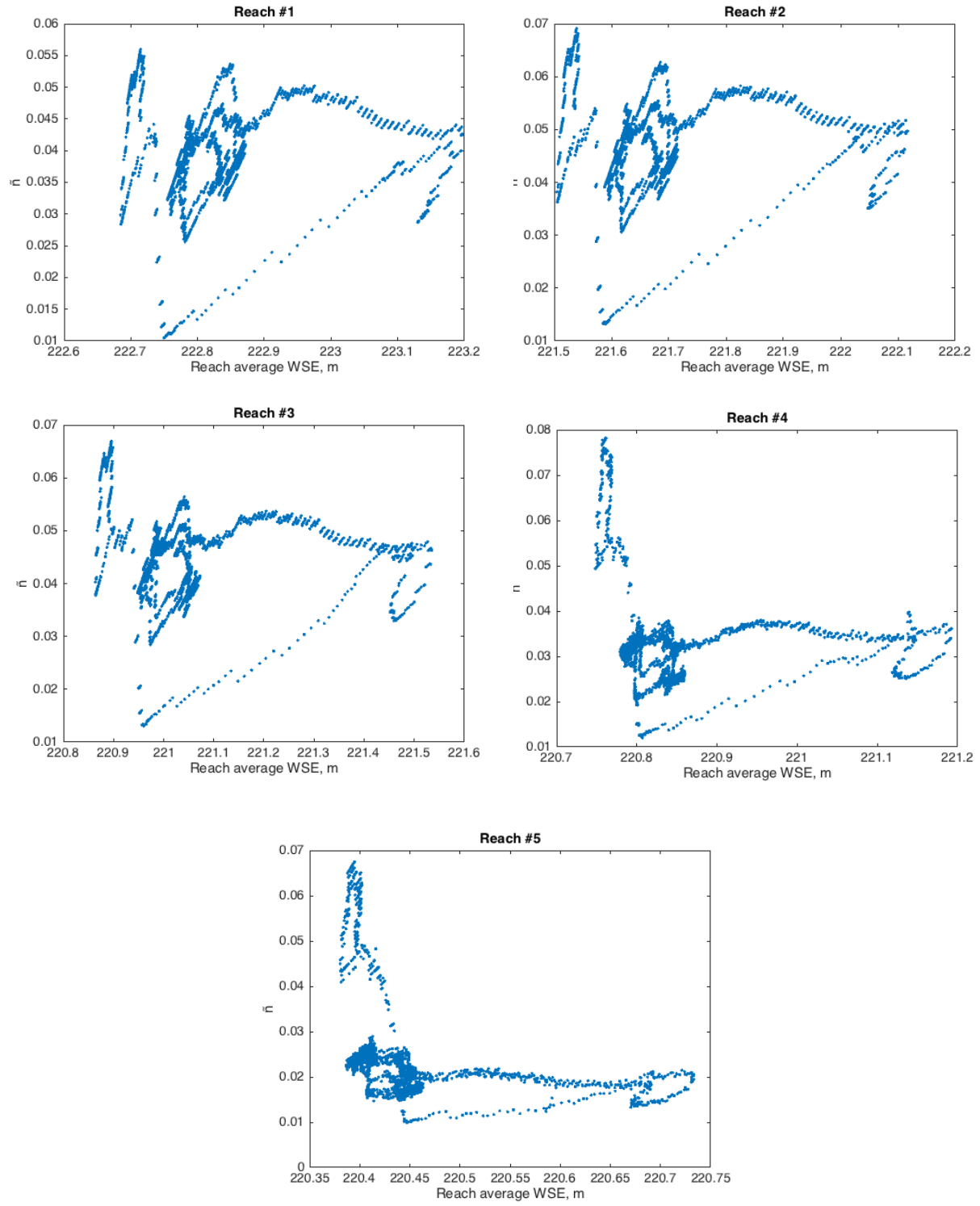


Figure 7:  $\tilde{n}$  vs. WSE.

## **DISCUSSION**

### *n* Variability

The noticeable difference between the upper three reaches and the lower two poses an intriguing problem. With a rather large variance in the downstream portion of the river, it is unknown if this is caused by actual river spatial variability or by error in evaluation of Manning's equation.

Areas of concern could be imprecise slope measurements, causing  $\tilde{n}$  to shift. This shift would propose that  $\tilde{n}$  varies far more than it actually does, resulting in inaccurate discharge products if the  $\tilde{n}$  was applied to a discharge algorithm.

## ONGOING AND FUTURE WORK

### Bathymetry Data

Initial bathymetry data were gathered using a Garmin 10272 depth sounder paired with a Garmin GPSMAP 441s chart plotter. The setup was mounted to the bottom of a kayak via PVC piping. This setup measured approximately 0.46 meters below the surface of the water. Combined with the minimum measurable depth of 0.3 meters, the smallest measurable depth was 0.76 meters. Measurements were taken at a frequency of 1 Hz using a four pass system. Passes were made over the thalweg and the two banks with an added zigzag pattern to maximize area covered. Combined with the coordinates and depth measurements recorded by the chart plotter were water surface elevations, taken in a similar manner as the previous year. Using depth measurements and water surface elevation, the bed elevation can be calculated.



*Figure 8: An image showing the process of collecting elevation data and bathymetry data. The instruments on the kayak were located both in the vessel and underwater, allowing for simultaneous collection of position via GPS and water depth measurements at a frequency of 1 Hz.*

Few bathymetry measurements were collected in areas of the river with shallower depths due to the initial design of the depth sounder rig on the kayak. A minimum measurement of 0.76 meters is too deep to accurately measure shallow parts of the river. These problems could be solved by reducing the depth that the depth sounder sits below water or using new equipment. More accurate measurements combined with higher coverage would provide a clearer look at the overall bathymetry. Ongoing research is attempting to solve this problem.

$A_0$  is still being measured. Since only preliminary data for reaches 4 and 5 have been gathered, continued research must take place to fill out missing data points and accurately show changes in  $\tilde{n}$ . The large values that were measured in the lower two reaches results in asymptotes at 0.1 at high flow. Future research should establish better measurements that show a more accurate correlation. Others will be able to use these measured  $A_0$  values to make further investigations into Manning's equation.

These methods were applied only to a small portion of one type of river, so this model may not work for other river types. Additional research in a broader selection of rivers could result in a more accurate algorithm for a range of land surface hydrology models.

## CONCLUSIONS

The research for this thesis shows that Manning's roughness Coefficient  $n$  does vary temporally over the course of the Olentangy River. In the downstream portions of the river,  $n$  varies by a factor of 2, while it varies significantly less in the upper reaches. Although  $n$  does vary, the cause of the variance is not clear. The results show different correlations between the upper three reaches before the dam and the lower two reaches below the dam. This split may show effects of the dam on river flow. Many factors can contribute to changes in the roughness coefficient, ranging from spatial variations to geologic and man-made causes. These models show that  $n$  does change based on spatial and temporal variations but other causes must be examined.



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